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ORIGINAL ARTICLE

A novel machine tool design approach based on surface generation simulation and its implementation on a fly cutting machine tool

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Abstract The paper presents a novel machine tool design approach which is based on the surface generation simulation and evaluation. This design approach bridges the gap between the machine tool performance and the surface topography generation, in view of the machine tool performance realizing the surface topography's prediction. The main influential factors of surface topography in multi-scale are discussed and modeled by different methods. In addition, by introducing the test software at the early machine tool design stage, the surface topography indicators' disparity between the simulation results and the design requirements are contrasted, which can indicate directions for the machine parameters' optimal design, such as the straightness and the dynamic performance. An ultra-precision fly cutting machine tool was designed under the guidance of this approach, and machining trials were carried out to evaluate and validate the approach and simulations presented.

Keywords Multi-scale surface simulation · Surface inspection · Ultra-precision machine tool · Design approach · Fly cutting

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1 Introduction

In order to deal with the energy crisis, many countries have carried out the research on the laser inertial fusion (LIF), such as the USA, France, the UK, Japan, and China. In the LIF system, the low-energy beam is amplified in the pre-amplifier module and then in the power amplifier, the main amplifier, and again in the power amplifier before the beam runs through the switchyard and into the target chamber to achieve nuclear fusion. The potassium dihydrogen phosphate (KDP) crystals are the key optical element in this system, which are widely used as harmonic frequency converters in the optical path, and can implement frequency multiplication and optical switching [1, 2]. In the LIF system, a large number of KDP crystals are urgently needed with strict processing requirements. In micro scale, it requires surface roughness values (Ra) of less than 3 nm in 0.01~0.12 mm, and in macro scale, it requires the root mean square (RMS) surface roughness of no more than 4.2 nm and the power spectral density (PSD) better than 15 nm^2 mm in 0.12~2.5 mm. The abovementioned specification is named PSD2, while a lower specification with the RMS of less than 6.4 nm and PSD better than 15 nm^2 mm in 2.5~33 mm is named PSD1. In addition, a gradient root mean square (GRMS) better than 11 nm/cm in the range over 33 mm is required [3]. However, the KDP crystal is hygroscopic and heat-sensitive so that traditional lapping and polishing methods are not applicable for processing this material. A feasible process to achieve the required surface quality is ultra-precision fly cutting [4]. Therefore, the specialized ultra-precision machine tools used for KDP crystals machining are urgently needed to develop. In the past several years, two generations of ultra-precision fly cutting machine tools have been designed and built in our laboratory [5–7]. However, the development of such machines are still at the nascent stage by past design experience. The design

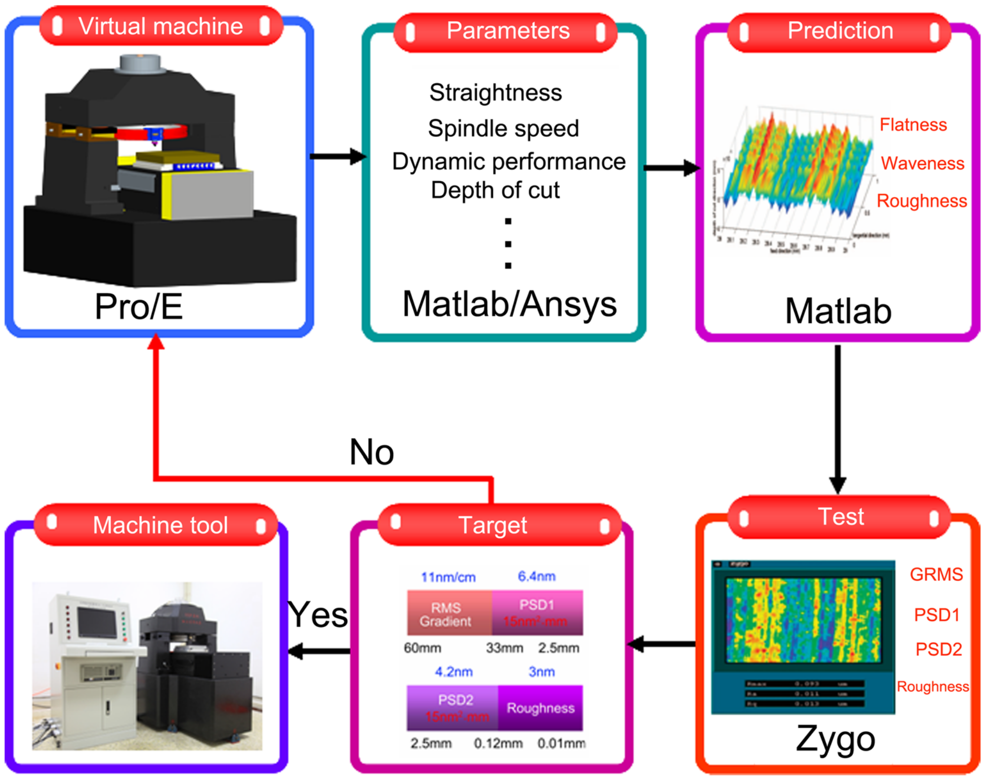

Fig. 1 The outline of the surface-generated simulation and evaluation-based machine tool design approach

specifications of the machine tool lack generic scientific approach and quantitative analysis, which cause the increase of development cost and time inevitably. In this paper, a novel surface generation simulation and evaluation-based design approach is proposed for the new generation machine tool design. The surface generation prediction has attracted a lot of research interests [8–11]. These researches were intended to predict the machined surface accurately, but did not provide the guidance for the machine tool design. The proposed approach attempts to provide a better understanding of the relationship between the surface generation and the machine tool design. On the basis of the influence of the machine tool performance on the surface generation, the test software is introduced to evaluate the surface prediction early at the machine tool design stage, and a theoretical basis for determination of design indicators of the machine tool performance is provided. This approach makes machine tool design at an effective and efficient manner and ensures the product/component surface finishes by the designed machine tool satisfy the functionality requirements.

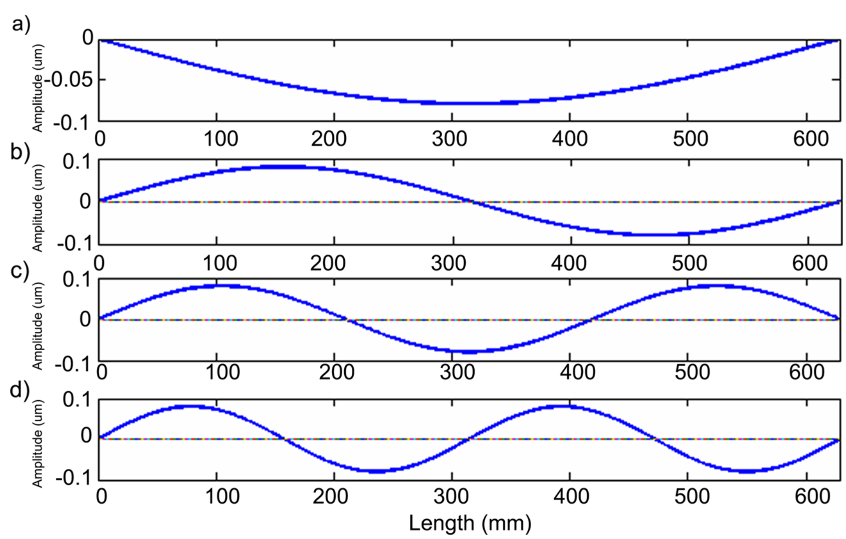

Fig. 2 Four typical shapes of the straightness

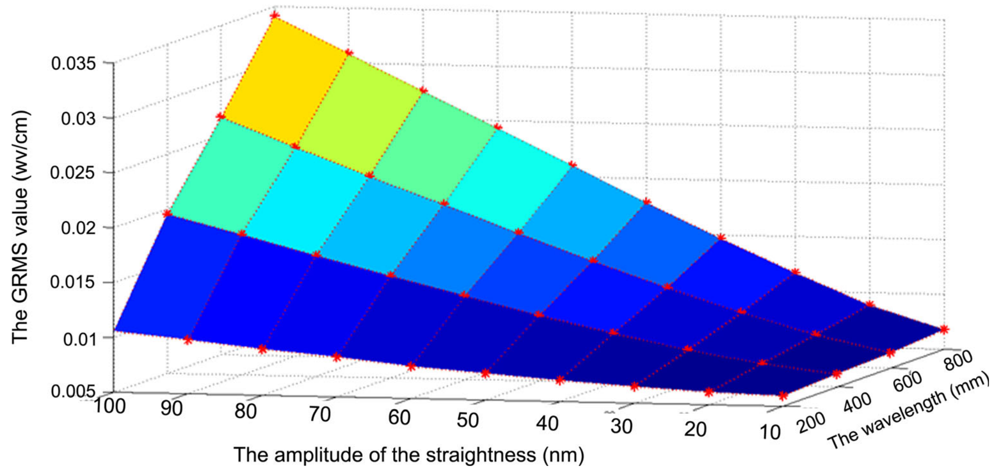

Fig. 3 The influences of slide straightness shape and amplitude on the GRMS

2 A surface-generated simulation and evaluation-based machine tool design approach

The schematic of the design approach based on the surface-generated simulation and evaluation is shown in Fig. 1. The first step for the machine tool design is the configuration design, and the following step is the initial determination of the design specifications, then these design specifications such as the straightness of the slide and dynamic performance of the machine tool are used to predict the surface morphology in multi-scale. The test software is used at the design stage to detect the predicted surface morphology in different scales. The test results are compared with the product requirements; if the test results satisfy the machining requirements, the prototype can be manufactured according to the design specifications used in the simulation model. Otherwise, the design specifications should be revised until the test prediction results satisfy the machining requirements. The following section will describe the design of the new generation specialized ultra-precision machine tool used for KDP crystals machining in details based on the proposed design method.

3 The design of the specialized ultra-precision machine tools used for KDP crystals machining

The structural type of the new generation machine tool is designed as the same as the first two generations as shown in Fig. 1. A bridge supports a vertical-axis spindle and fly-cutter over a horizontal-axis slide. Mounted to the horizontal slide is a vacuum chuck that clamps the workpiece. The surface to be machined lies in a horizontal plane. In the KDP crystal machining requirements, the GRMS and PSD1 targets are difficult to achieve, due to the large evaluation interval. Therefore, this study mainly focuses on these two indicators to design the machine tool.

3.1 The machine tool design considering the GRMS target

Taking into account the structure type and kinematic chain of the machine tool, it can be noted that the GRMS of the machined surface is affected by the straightness of the slide and the dynamic stiffness of the machine tool.

Currently, the straightness of the slide is realized by the scraping and polishing processes, and it is difficult to describe straightness shape by a close form expression, but the basic shape is sine wave-like curve. In order to analyze the influence of the straightness on the GRMS quantitatively, the straightness is described by Eq. (1) approximately [12, 13]:

$$y(x) = A\sin\left(\frac{2\pi}{T}x\right) \tag{1}$$

where A is the amplitude of the straightness and T is the wavelength of the function. Figure 2 shows four typical shapes of the straightness. In the whole length of the slide, they have half to two periods, respectively.

In order to evaluate the influence of the shape and amplitude of the slide straightness on the GRMS, the simulations to the four typical straightness shapes with different amplitudes are carried out. Figure 3 shows the GRMS trends change with

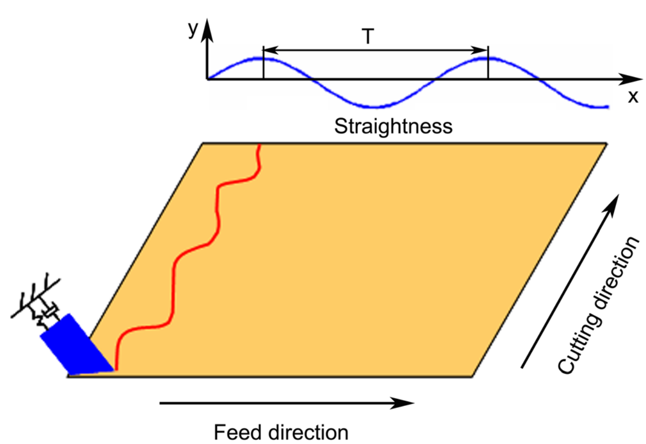

Fig. 4 The schematic diagram of the cutting process

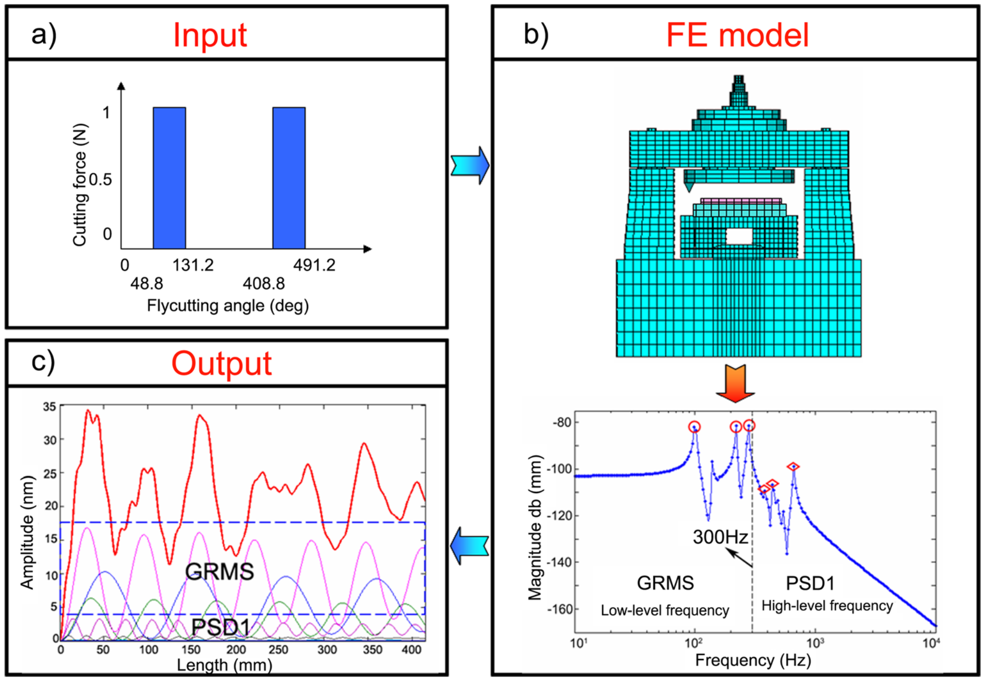

Fig. 5 The influence of the machine tool dynamic performance on the machined surface

the straightness shape and amplitude. It can be noted that the GRMS increases with the decrease of the wavelength, and the increase of the amplitude, respectively. And the wavelength of the straightness has a more significant effect on the GRMS especially at higher straightness amplitude. It is because the GRMS is mainly affected by the waviness gradients and the distribution density. Under the same wavelength, when the amplitude increases, the distribution density does not change, and the waviness gradients only changes slightly, so the GRMS has a slight increase. While under the same amplitude, the waviness gradients increase with the wavelength decreases, and the distribution density changes significantly, resulting in a large change of GRMS.

This trend indicates that in the slide design, emphasis should be put not only on the amplitude of the straightness but also on the shape of the straightness. When reducing the amplitude of the straightness, the wavelength should be increased as long as possible. The shape of the straightness shown in Fig. 2a is the best shape in the slide designing.

As shown in Fig. 4, the profile caused by the straightness combining with the large period waviness affects the GRMS of the machined surface. The following text will discuss the waviness caused by the dynamic performance of the machine tool.

In order to obtain the influence of the machine tool dynamic performance on the machined surface, an accurate FE model is built for the machine tool designed in Fig. 1. The input is the periodically interrupted cutting force and the output is the vibration of the tool which will form the waviness on the surface. The relationship between the period of the waviness and dynamic performance can be expressed by [14],

$$T_D = \frac{\pi d \times n_0 \times \cos\theta}{60\omega_n} \tag{2}$$

Where d denotes the diameter of the flying head (d=630 mm), n_0 denotes the speed of spindle (n_0=300 rpm), θ denotes the maximum angle of the tangent direction in cutting process (θ=0°), T_D denotes the period of the vertical stripes, and ω_n denotes the natural frequency of the machine tool. According to Eq. (2), the natural frequency less than 300 Hz, T_D to be larger than 33 mm, which affects GRMS, is termed low-level frequency. While the natural frequency larger than 300 Hz, T_D to be less than 33 mm which affects the PSD1, is termed low-level frequency.

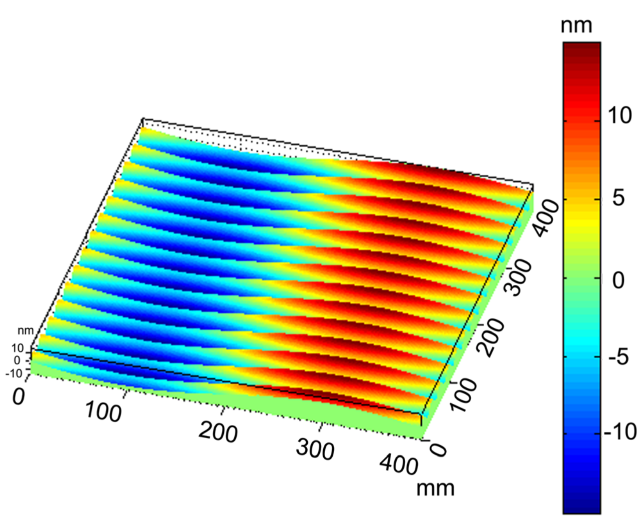

Fig. 6 The simulation surface of the workpiece

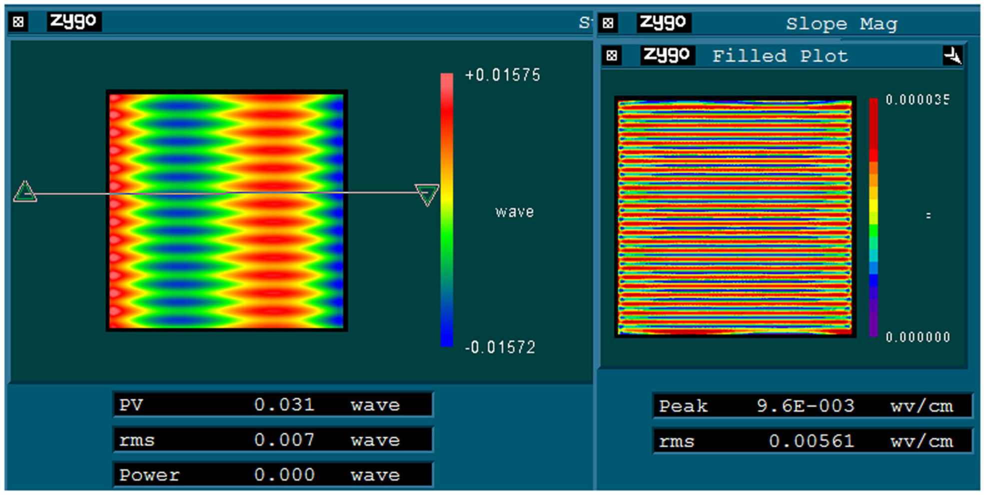

Fig. 7 The GRMS test result of the simulated surface

Figure 5b shows the dynamic performance of the machine tool; at the frequency range close to the natural frequency of the machine tool, the dynamic stiffness decreases largely, which leads to the increase of the relative displacement between the cutting tool and the workpiece, resulting in the waviness in cutting direction.

The output in Fig. 5c shows the integral relative displacement between the cutting tool and the workpiece under the periodically interrupted cutting force as shown in Fig. 5a and the relative displacement between the cutter tool and the workpiece caused by the vibration of the machine tool under the natural frequencies. It can be noted that the response under the low-level natural frequencies has long wavelength larger than 33 mm with large amplitude, which will affect the GRMS. The response under the high-level natural frequencies has short wavelength smaller than 33 mm with small amplitude, which will affect the PSD1.

Figure 6 shows the simulation surface coupling the slide straightness and the waviness caused by the machine tool dynamic performance. In this simulation, the straightness shape is as shown Fig. 2b, and the value is 0.01 μm/420 mm; the dynamic performance is as shown in Fig. 5. The simulation result is transformed into the format which can be read by the test software. Figure 7 shows the test result of Fig. 6. It shows that the GRMS value of the simulation surface is 3.55 nm/cm.

3.2 The machine tool design considering the PSD1 target

In the above analysis, we analyzed the influence of the straightness on the GRMS, and found that under the same amplitude, the straightness shape as shown in Fig. 2a is the best. Therefore, in this study, the shape of straightness is selected as shown in Fig. 2a, and the amplitude is decided as 0.01 μm/420 mm, according to the current level of technology. The following shows the influence of the machine tool dynamic performance on the GRMS and PSD1. Figure 8 shows the GRMS trends change with different low-level frequency dynamic performance of the machine tool. To test the flatness target GRMS, the low pass filter is used and the high-pass frequency is 0.0303 mm^{-1}. From Fig. 8a, it can be found that when the wavelength is less than 33 mm, it is not in the evaluation interval of GRMS and is filtered out by the high-pass filter, so it only has a little influence on the GRMS. When

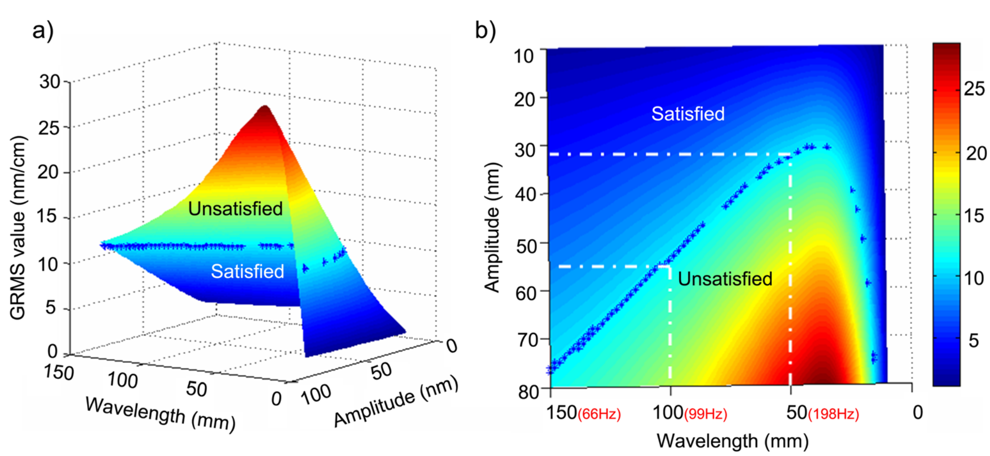

Fig. 8 The influence of the dynamic performance of the machine tool on GRMS

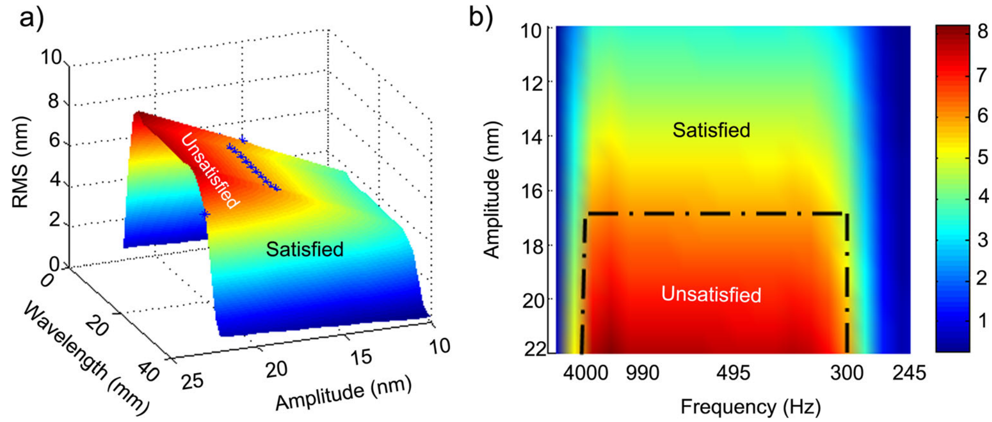

Fig. 9 The impact of the dynamic performance of the machine tool on PSD1

the wavelength is near 33 mm, it enters the evaluation interval of GRMS, and has the largest distribution density. Therefore, the GRMS reaches the maximum value. With a further increase of the wavelength of waviness, the distribution density gradually reduces, so its impact on GRMS weakens and GRMS value emerges decreasing trend.

In Fig. 8b, it shows that when the low-level frequency of the machine tool is less than 66 Hz, to satisfy the requirements of the GRMS, it needs a response value not larger than 75 nm. When the low-level frequency of the machine tool is less than 99 Hz, to satisfy the requirements of the GRMS, it needs a response value not larger than 55 nm. When the low-level frequency of the machine tool is less than 198 Hz, to satisfy the requirements of the GRMS, it needs a response value not greater than 32 nm.

It shows that with the low-level frequency of the machine tool approaching to 300 Hz, the requirements of the response value become less significant. It indicates that in the machine design process, the designers can not pursue blindly to improve low-level frequency of the machine, but should take full account of the relationship between the frequency and response amplitude to achieve the satisfied GRMS.

Figure 9a shows the influence of the high-level frequency of the machine tool on the PSD1. In order to get the PSD1 target, the band pass filter is used; the pass frequency is between 0.4 and 0.0303 mm^{-1}. It shows that the wavelength not in the PSD1 evaluation interval has slight impact on the PSD1. The PSD1 is mainly affected by the amplitude of the waviness, and the PSD1 value increases with the waviness amplitude even within evaluation interval. And the wavelength has slight impact on the PSD1. Taking into account the large evaluation interval from 300 to 4000 Hz, it is difficult to avoid the high-level frequency of the machine tool in this region, and in the evaluation interval, the frequency has slight impact on the PSD1; therefore, in the machine design process, there is no significance to optimize

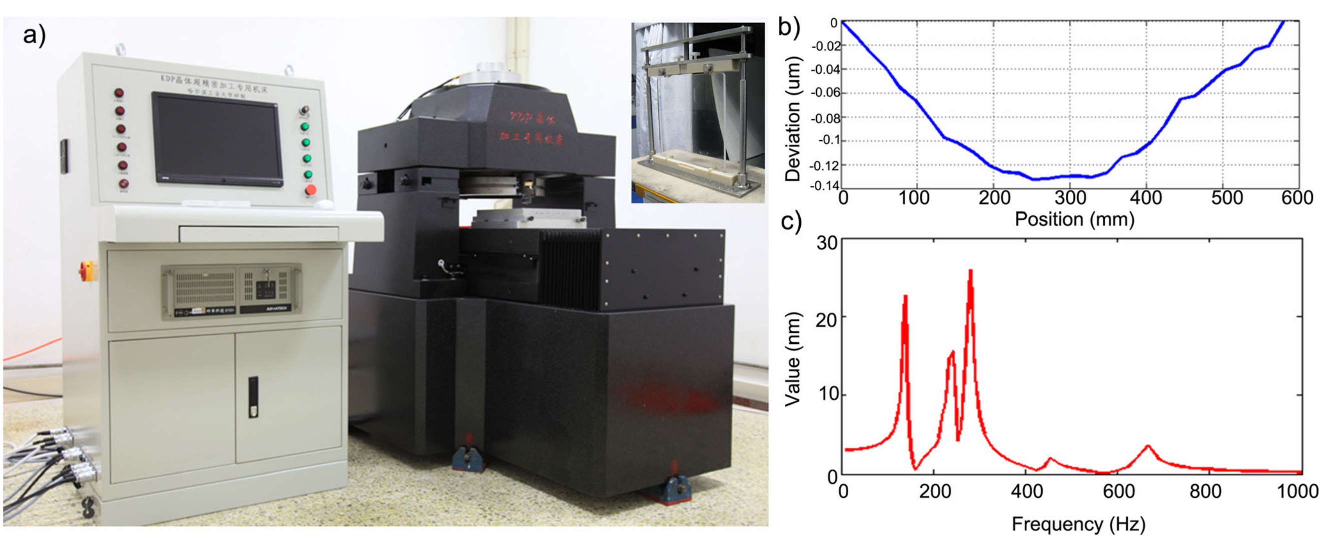

Fig. 10 The machine tool and its performance. **a** The new generation fly cutting machine tool; **b** the straightness of the slide; **c** the dynamic response of the machine tool

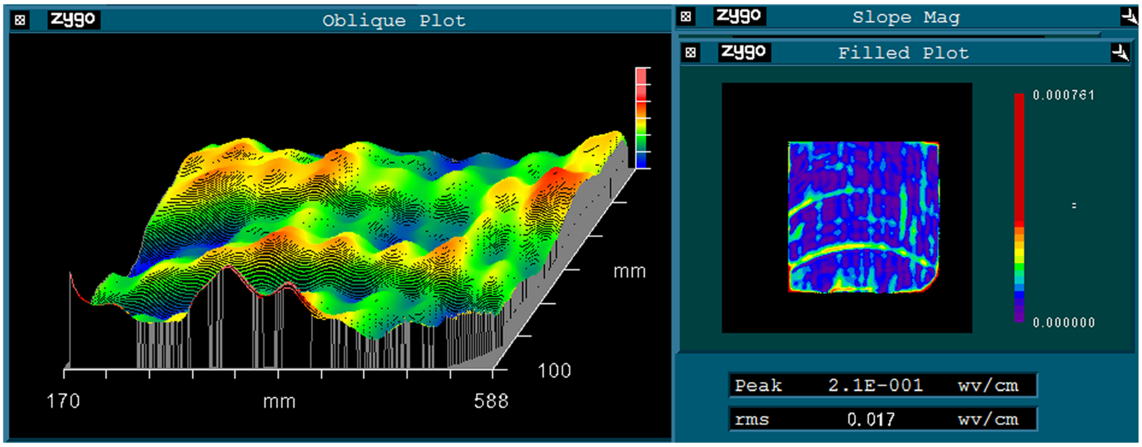

Fig. 11 The test result of GRMS

the high-level frequency of the machine tool, but should take full account of the amplitude of the dynamic response. Figure 9b shows that to satisfy the PSD1, the maximum amplitude should be less than 17 nm.

4 The machine tool designed and the machining trials

Figure 10a shows the ultra-precision machine tool designed by the proposed method and the KDP crystal machined by this machine tool. Figure 10b shows the straightness of the slide in the working length is less than 0.01 μm. Figure 10c shows the dynamic response of the machine tool, and it can be noted that the natural frequency of the machine tool in the low-level frequency is in the region from 100 to 300 Hz; the amplitudes are less than 30 nm, while in the high-level frequency, the amplitudes are less than 10 nm. According to the analysis above, the dynamic performance of the machine tool can satisfy the machining requirements.

Machining trials were carried out on the ultra-precision fly cutting machine tool whose performance is used in the simulation model, to validate the model and the simulation. The following machining parameters are used in the processing experiments: depth of cut of 15 μm, feed rate of 60 μm/s and a spindle rotational speed of 390 r/min, tool nose radius of 5 mm, tool rake angle of −25°, and front clearance angle of 8°. The experimental results are examined by a 3D rough surface tester, Wyko RST-plus (Veeco Metrology Group, Santa Barbara, CA, USA), which has a 500 mm vertical measurement range and 3 nm vertical resolution. The test result is read by the software Zygo. The measurement results with only tip, tilt, and piston removed are shown in Figs. 11, 12, and 13. From Fig. 11, it can be noted that the GRMS of the machined surface is 0.017 wv/cm (10.76 nm/cm), which is less than the product requirement (11 nm/cm). Figure 12 shows that the roughness of the machined surface is 3.8 nm (RMS). Figure 13 shows that the PSD1 is bellow the not-to-exceed line of the product. The test results are in good agreement with the

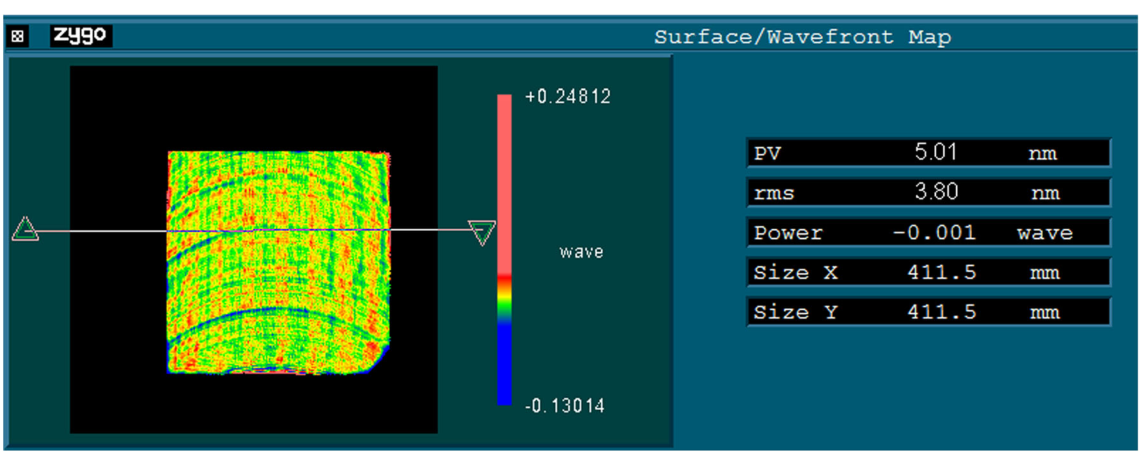

Fig. 12 The test RMS result in PSD1 region

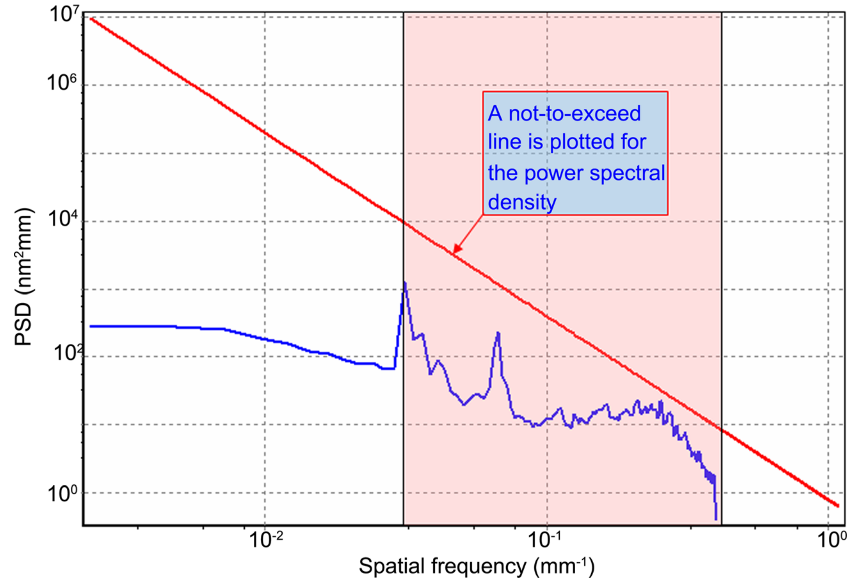

Fig. 13 The test PSD result in PSD1 region

analytical and simulation results, which verifies the validity and reliability of the simulation model.

5 Conclusions

This paper presents a novel machine tool design approach based on the surface simulation and evaluation. This design approach is used to design an ultra-precision fly cutting machine tool for KDP crystal machining. The following conclusions can be drawn.

1. The proposed design method bridges the gap between the surface topography prediction and the machine tool design by introducing the test software early at the machine tool design stage. The simulation surface provides information for the machine parametric design. It can quantitatively analyze the influence of machine performance indicators such as the straightness, the dynamic stiffness, and the natural frequency on the surface topography, and provide a better understanding of the further design of the performance of ultra-precision machines.
2. For the slide straightness design of the fly cutting machine tool, the wavelength of the straightness should be designed as long as possible and amplitude as small as possible.
3. To achieve the satisfied GRMS, in the machine design process, the designers should not pursue improving low-level frequency of the machine, but should take full account of the relationship between the frequency and response amplitude.
4. In order to satisfy the PSD1, in the machine design process, there is no significance to optimize the high-level frequency of the machine tool, but should take full account of the amplitude of the dynamic response, and the maximum amplitude of the high-level frequency should be less than 17 nm.
5. These experimental tests evaluate and validate that the proposed design approach is effective and efficient in optimizing the design of the fly cutting machine tools leading to improved operational performance. It indicates that the proposed design approach can be used as a powerful tool for supporting the full design process from the dynamic point of view, which also enables the machine design to be optimized efficiently and effectively.

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Conflict of interest The authors declare that there is no conflict of interest.

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